THE NUMBER FLUX OF SNOW CRYSTALS AT THE GROUND

K. L. S. GUNN

McGill University, Montreal

ABSTRACT

Many measurements of the snowfall rate R and the average mass per crystal $\overline{m}$ have provided values of $R/\overline{m}$, the number of snow crystals reaching unit area of the surface per unit time. A typical number is 1 per cm.^{2} per sec. Over a whole season's data, the flux is proportional to the snowfall rate. Specifically, two-thirds of the measurements lie within a factor two of a locus $R/\overline{m}$ (cm.$^{-2}$ sec.$^{-1}$) $=1.5\ R^{1.0}$ where R is in millimeters of water per hour. Thus the principal contribution to any increase in the snowfall rate is the formation of new crystals, rather than the growth of existing ones.

1. INTRODUCTION

The number of snow crystals arriving in unit time on unit area at the surface is an important parameter of cloud physics. The primary source of snow crystals is the freezing of supercooled cloud droplets aloft. Rough estimates of the number of freezing events there and of the number of crystals arriving at the ground (see Mason [1], for example) suggests that the primary source is not enough and that some secondary process such as splintering is multiplying the primary n mber, perhaps by as much as several factors of 10. There has been and there continues to be considerable work done on freezing nucleation which should lead to better estimates of the number of freezing events aloft. Reported here for comparison are measurements of the crystal flux at the surface.

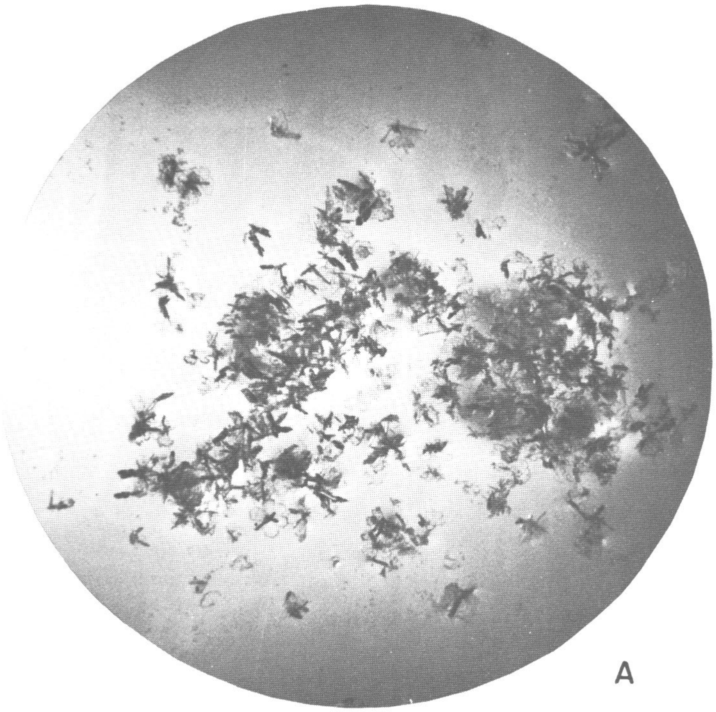
The principal problem in making measurements of the number of crystals per second arriving on unit area at the ground was to find a way of collecting a sample of crystals from which a count could be made. In the first place the sample had to be collected without breaking up the individual crystals. Then, since falling snow almost always consists of aggregates of crystals, the technique had to provide some way of taking the aggregates apart in order to make the count. After experimenting with a number of different collectors, we found that we could do both these things by collecting the crystals in a petri dish containing a 5-mm.-deep layer of liquid paraffin at a temperature of about $-10°$ C.

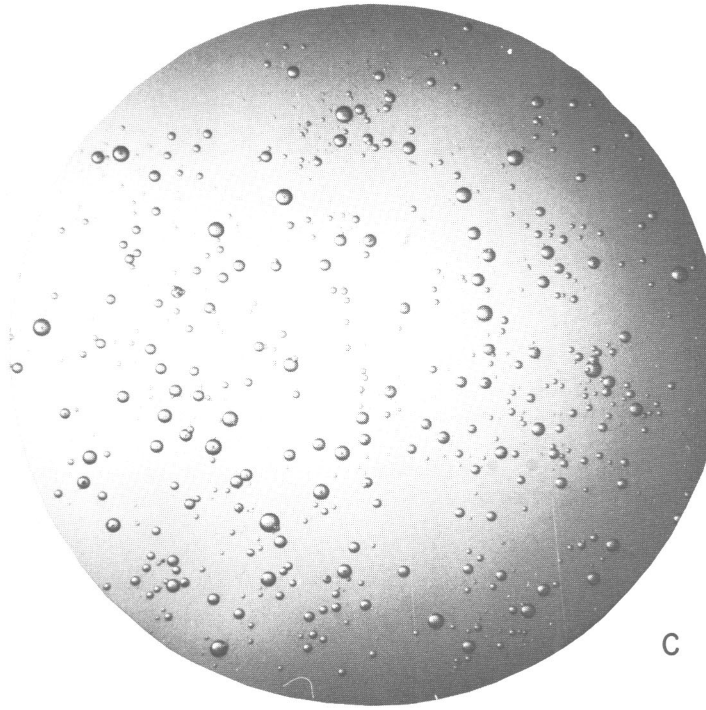
The number flux can be calculated directly from the count combined with the area of the dish and the exposure time, but the small volume sampled makes this procedure unreliable. Thus, we decided to determine the number flux indirectly. From each sample the average mass per crystal $\overline{m}$ was measured. At the same time, a continuous measurement of the rate of snowfall R was being made, and the ratio $R/\overline{m}$ gave the flux, the number of crystals per unit area per second.

2. SAMPLING, OBSERVING, AND RECORDING

To catch a snow sample, a petri dish containing the cold paraffin was exposed to the snow falling in a courtyard about 60 ft. across and enclosed on three sides. Exposure times varied with the type and intensity of the snowfall, but were of the order 10–20 sec. After exposure, the dish was carried a few feet indoors where it was placed in a "deep freeze" unit to be viewed and photographed through a modified binocular microscope. A negative lens (-0.5 dioptre) had been placed in each arm so that the real images formed by the objective lenses were carried beyond the tops of the tubes that no mally hold the eyepieces. On one tube the eyepiece was replaced by a 35-mm Leica camera-back positioned so that the real image plane coincided with the film. On the other tube was a suitably positioned micrometer eyepiece. A photograph was taken (fig. 1A), with the microscopic objective at its lowest magnification ($\times$ 0.8). On the film the region of best focus was a circle of 2.0-cm. diameter corresponding to a 2.5-cm. diameter field in the sample dish. All the measurements were made using only the crystals within that circle. Usually four photographs of four different parts of the dish were taken. If the sample consisted of separated single crystals they were then melted by holding the end of a heated test tube over the sample area. The resulting droplets were then photographed (fig. 1C). If, on the other hand, the sample contained aggregates, a cold plastic probe drawn out to a fine point was passed through the aggregate of crystals after photograph (A) was taken. This could be done several times, and was done only as often as was necessary to separate the crystals sufficiently so that they could be counted in the photograph (B) that was then taken (fig. 1B).

The water drops suspended in the cold paraffin oil were assumed to be spherical during the 1 min. or less between melting and the time when photograph (C) was taken. After several minutes some drops began to reach the





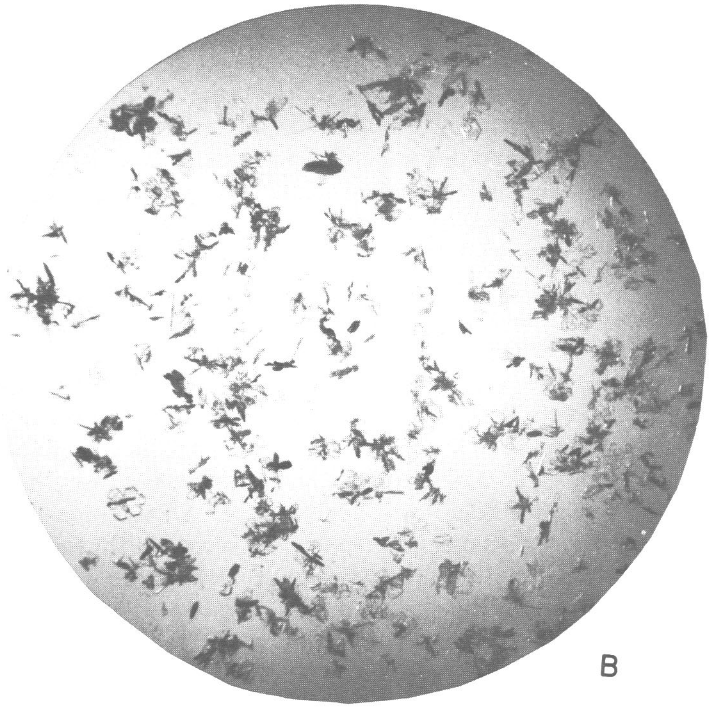


FIGURE 1.—Photograph of the crystals lying in a 2.5-cm. diameter portion of the petri dish exposed at 2005 hr., Feb. 16, 1962. (A) Taken immediately after collecting sample. (B) After crystals separated by gentle stirring. (C) Melted drops formed from crystals in (B).

there.

3. THE AVERAGE MASS PER CRYSTAL $\bar{m}$ AND THE SNOWFALL RATE R

Analysis of the photographs was done on projected images of the 35-mm. negatives enlarged by a factor of 10. The number of individual crystals n was counted on photograph (A) in the case of single crystals, (B) in the case of aggregates. On photograph (C) the diameter of each drop was measured, its mass tabulated, and so the total mass M of the sample obtained. The ratio M/n gave the average mass per particle $\bar{m}$ in the sample.

The values of $\bar{m}$ measured in the six storms are plotted as a function of time in figure 2. Each value of $\bar{m}$ is indicated by a cross and corresponds to the average crystal mass in one 2.5-cm. diameter region of the 10-cm. petri dish. Thus for each point marked with an (×) in figure 2 there was a set of photographs such as figure 1. When occasionally more than four points are shown for one time, two dishes were exposed. In figure 2, the average of the several values has been used as representative. The maximum departure from this mean was never more than a factor 2, and generally less than a factor 1.5. All 84 values of $\bar{m}$ lie between about 5 and 50 μgm. The range in any one storm was usually less than this. Measurements of individual crystal masses reported by Nakaya [2] extended from a few to about 150 μgm. and so our mean values of 5 to 50 μgm. fit well into his range.

The snowfall rate R was measured continuously using a pulsed light device that was under development at that time. With this device the falling snow was illuminated about 50 yd. to the southwest of the courtyard where the samples were collected. Light scattered at 90° by the illuminated snow was detected by a photocell, the signal amplified and displayed on a strip chart recorder. Calibration of this record was provided by comparison with a heated tipping-bucket gage. (In the last storm Apr. 1–2, this high-resolution device was not in operation, so that for that storm we had to make do with

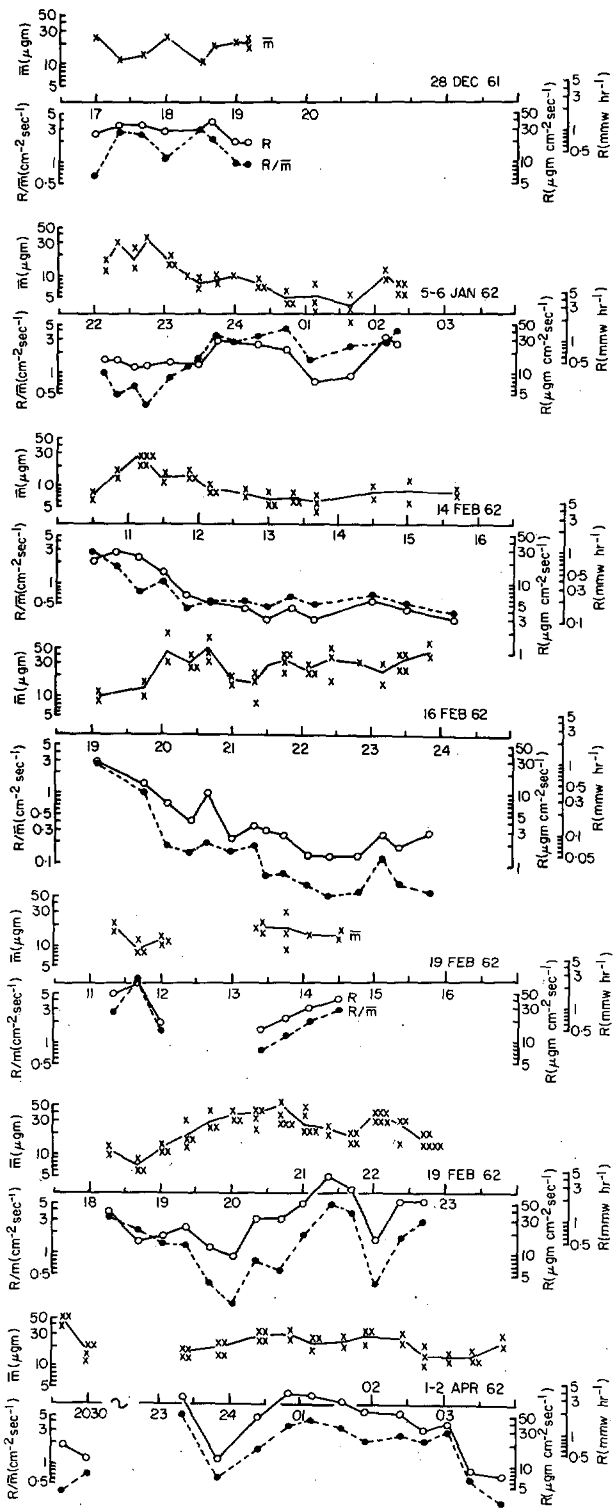


FIGURE 2.—Plots against time during six storms of m, the average mass per crystal (above the time axis), and R, the snowfall rate (below the time axis, open circles). The flux $R/\overline{m}$ is indicated by the full circles joined by a broken line. The lines between the points serve merely to join measured values of the quantities in each case, and do not represent the actual behavior of the variables. The snowfall rate R, for instance, which was measured continuously, underwent considerable changes between the times of measurement. The ordinate scales are all logarithmic and the same for each storm. Note, however, that the scales for R and $R/\overline{m}$ had to be extended to lower values for the later measurements in the storms of Feb. 14 and Feb. 16.

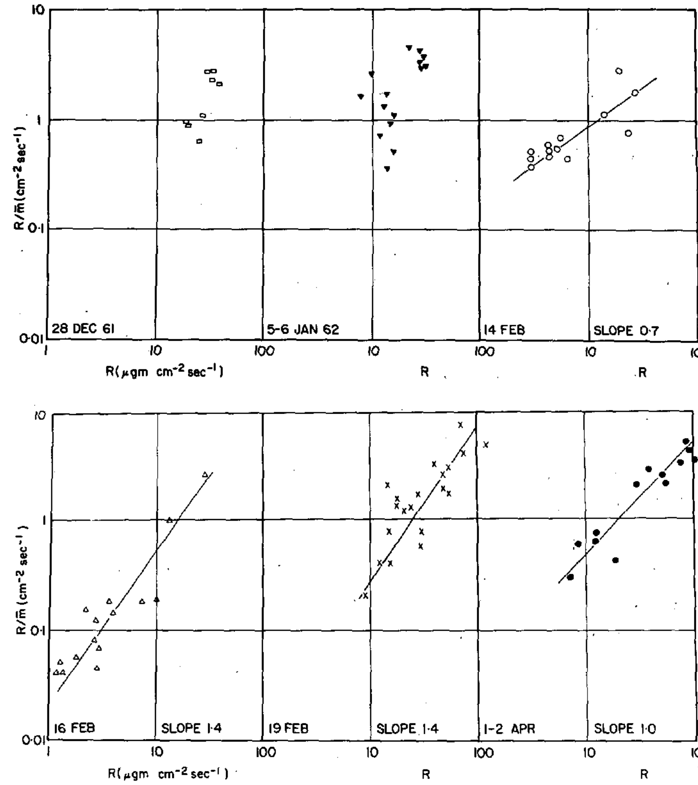


FIGURE 3.—Each of the six graphs is a log-log plot of crystal flux $R/\overline{m}$ against snowfall rate R for each of the six storms.

TABLE 1.—*Summary of measurements*

Storm	Sampling period (GMT)	Duration (hr.)	Number of sample times	Range in $\overline{m}$ (μgm.)	Range in R (μgm. cm.$^{-2}$ sec.$^{-1}$)	Range in $R/\overline{m}$ (cm.$^{-2}$ sec.$^{-1}$)
1. Dec. 28....	1700-1915	2¼	8	11-25	20-40	0.6-3
2. Jan. 5-6....	2200/5-0230/6	4½	15	4-38	8-32	0.3-5
3. Feb. 14....	1030-1530	5	13	6-28	3-30	0.4-3
4. Feb. 16....	1900-2400	5	14	10-50	1.3-13	0.04-1.0
5. Feb. 19....	1100-1200 1330-1430 1800-2300	7	20	7-50	9-120	0.2-8
6. Apr. 1-2...	2000-2030 2300-0400	5½	14	14-45	7-100	0.3-5
Total....		30	84			

the record from the heated gage itself.) In figure 2 the values of R at the time of measurement are indicated by open circles and are read against the logarithmic scales at the right, in either μgm. cm.$^{-2}$ sec.$^{-1}$ or in mm.w. hr.$^{-1}$ (millimeters of water per hour). The rates range from 0.05 mm.w. hr.$^{-1}$ to nearly 5 mm.w. hr.$^{-1}$ and so cover a factor of 100 compared with the factor 10 covered by the average mass $\overline{m}$. The storm of Feb. 16 is notable for the low rates, below 0.1 mm.w. hr.$^{-1}$, during the sampling period. In the Feb. 19 and Apr. 1–2 storms on the other hand, there were the highest rates, with one measurement made when it was snowing at greater than 4 mm.w. hr.$^{-1}$

The measurements that are plotted in figure 2, and in figure 3 which follows, are summarized in table 1.

4. THE AVERAGE FLUX OF CRYSTALS $R/\overline{m}$ AND RELATIONS AMONG $\overline{m}$, R, AND $R/\overline{m}$

The third plot in figure 2 is $R/\overline{m}$, the average flux of crystals. The values are shown in full circles with adjacent points joined by a broken line. They are read against the log scale at the left. The flux of crystals on most days lies between about 0.3 and 3 cm.$^{-2}$ sec.$^{-1}$, with 1 cm.$^{-2}$ sec.$^{-1}$ a representative value. The exception was Feb. 16 when all but two values were less than 0.3 cm.$^{-2}$ sec.$^{-1}$

The plots against time of the measured quantities $\bar{m}$ and R in figure 2 do not show any notable correlation. Except in the first two storms the variations in $\bar{m}$ tended to be small compared with those in R. This can be seen most readily in the relatively small variation in the separation between the two lower curves $R/\bar{m}$ and R compared with the variation in either curve. When $\bar{m}$ does vary by as much as a factor 10, as for example during the storm of Jan. 5–6 the changes in R appear unrelated.

One way to investigate a possible relation between $\bar{m}$ and R is to look at plots of log $R/\bar{m}$ against log R. Any departure from a simple proportionality would indicate that $\bar{m}$ is dependent on R. In figure 3 separate plots are given for each storm. No attempt has been made to draw a locus through the data for the first two (Dec. 28 and Jan. 5–6) because of their limited range in R. For the remaining four storms, however, loci of best fit have been drawn by eye through the data. Their slopes are respectively 0.7, 1.4, 1.4, and 1.0. (On a plot of log $\bar{m}$ against log R these slopes would be $+0.3$, -0.4, -0.4, and 0.) The scatter on these plots is generally less than a factor two in $R/\bar{m}$, while the range in R is a factor 10 or more, so that each locus is reasonably well defined. It would be difficult for instance, to change the individual loci for the storms of Feb. 14, 16, and 19 to a slope of 1.0. Thus it appears that in the storm of Feb. 14 the average mass per crystal tended to increase with increasing snowfall rate. In the storms of Feb. 16 and 19 it decreased slightly, and in the storm of Apr. 1–2 it was effectively constant.

The number of data in any one storm is quite small; there is considerable scatter and the range of each variable is limited. It could be argued that the variations in index should not be taken too seriously. In figure 4 the 84 data from the six storms are all assembled on one plot of log $R/\bar{m}$ against log R. On that plot a line of slope 1.0 fits about as well as any, especially if we give less weight to the data from Feb. 16 at snowfall rates of less than 0.1 mm.w. hr.$^{-1}$ The equation of the locus is

$$R/\bar{m}\ (\text{cm.}^{-2}\ \text{sec.}^{-1})=1.5R^{1.0}$$

where R is in mm.w. hr.$^{-1}$ Individual values depart from the locus by as much as a factor 4, but approximately two-thirds of them lie within a factor 2 of it. Thus, within these limits, the average flux of crystals over a whole season is directly proportional to the snowfall rate, and within the same factors the average mass per crystal is effectively constant (at 18.2 μgm.).

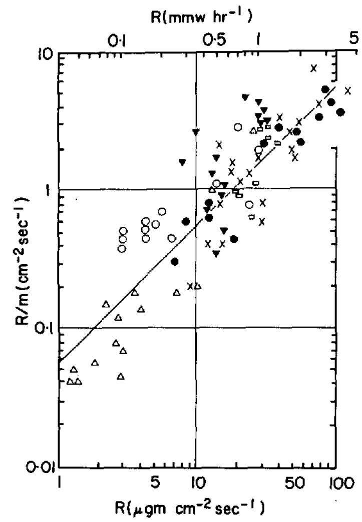


FIGURE 4.—All of the data from the six graphs in figure 3 are plotted against the same coordinates. A locus of slope 1.0, indicating proportionality between flux and snowfall rate, has been fitted through the data. Its equation is $R/\bar{m}$ (cm.$^{-2}$ sec.$^{-1}$)$=1.5$ $R^{1.0}$ where R is in mm.w. hr.$^{-1}$

5. SUMMARY AND CONCLUSIONS

The average flux of snow crystals $R/\bar{m}$ at the surface has been derived from 84 measurements of the snowfall rate R and the average mass per single crystal $\bar{m}$ in six storms in the winter of 1962. Over the range of snowfall rates 0.1 to 5 mm.w. hr.$^{-1}$ comprising most of a season's snow, the flux varies from about 0.2 to about 10 cm.$^{-2}$ sec.$^{-1}$ Over a number of storms in a season the flux is proportional to the snowfall rate, the average locus being given by $R/\bar{m}$ (cm.$^{-2}$ sec.$^{-1}$)$=1.5R^{1.0}$ where R is in mm.w. hr.$^{-1}$ In individual storms there is some evidence that the index on R may vary either way from 1.0, implying in some storms a slight increase and in others a slight decrease of the average mass per crystal with increasing snowfall rate.

The proportional relationship that holds on the average implies that when an increase in snowfall rate occurs, the principal contribution to that increase is the formation of new crystals rather than the growth of existing ones.

ACKNOWLEDGMENTS

The work described in this paper is dependent on many careful observations, which had to be made at the time it was snowing rather than at the observers' convenience. These observations, including the dissection of snow aggregates and preliminary analyses, were begun by Mr. Laurence Outhouse and continued with considerable dedication by Mr. Kenneth Latchford. The assembly and final analysis of the data were carried out by the author at the Cavendish Laboratory, Cambridge, while holding National Research Council of Canada Senior Research Fellowship. Many helpful and incisive discussions with the author's senior colleague at McGill, Professor J. S. Marshall, are gratefully acknowledged.

REFERENCES

1. B. J. Mason, "The Physics of Clouds," *Oxford Monographs on Meteorology*, Oxford University Press, London and New York, vol. 1, 1957, 481 pp.
2. U. Nakaya, *Snow Crystals, Natural and Artificial*, Harvard University Press, Cambridge, 1954, 510 pp.

[*Received July 1, 1967*]